AD-A167 032 CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION(U) ARIZONA UNIV TUCSON ENGINEERING EXPERIMENT STATION D M MCELIGOT 29 NOV 85 1248-11 N00014-75-C-0694 1/1

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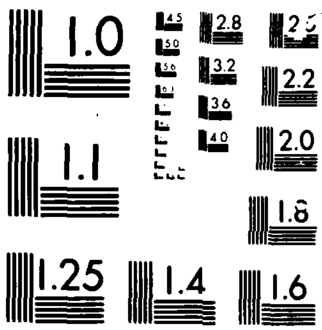

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FINAL REPORT

Contract N00014-75-C-0694; NR-097-395

CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION

Donald M. McEligot
Aerospace and Mechanical
Engineering Department

29 November 1985

Final report for period:
1 April 1974 - 30 September 1985

Prepared for:

OFFICE OF NAVAL RESEARCH
Code 1132p
800 N. Quincy Street
Arlington, Virginia 22217

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

- **1a. REPORT SECURITY CLASSIFICATION:** Unclassified
- **1b. RESTRICTIVE MARKINGS:**
- **2a. SECURITY CLASSIFICATION AUTHORITY:**
- **2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:**
- **3. DISTRIBUTION/AVAILABILITY OF REPORT:** Approved for public release; distribution unlimited; reproduction in whole or in part is permitted for any purpose of the U.S.Govt.
- **4. PERFORMING ORGANIZATION REPORT NUMBER(S):** 1248-11
- **5. MONITORING ORGANIZATION REPORT NUMBER(S):**
- **6a. NAME OF PERFORMING ORGANIZATION:** Engineering Experiment Station, College of Engineering
- **6b. OFFICE SYMBOL** *(If applicable)*:
- **6c. ADDRESS** *(City, State and ZIP Code)*: University of Arizona, Tucson, Arizona 85721
- **7a. NAME OF MONITORING ORGANIZATION:** Office of Naval Research, Bandolier Hall West - Room 204
- **7b. ADDRESS** *(City, State and ZIP Code)*: University of New Mexico, Albuquerque, New Mexico 87131
- **8a. NAME OF FUNDING/SPONSORING ORGANIZATION:** Office of Naval Research
- **8b. OFFICE SYMBOL** *(If applicable)*:
- **8c. ADDRESS** *(City, State and ZIP Code)*: Code 1132p, 800 N. Quincy Street, Arlington, Virginia 22217
- **9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:**
- **10. SOURCE OF FUNDING NOS.**

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
NR-097-395			

- **11. TITLE** *(Include Security Classification)*: CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION (U)
- **12. PERSONAL AUTHOR(S):** McEligot, Donald M., P. O. Box 4282, Middletown, Rhode Island 02840
- **13a. TYPE OF REPORT:** Final
- **13b. TIME COVERED:** FROM 4/1/74 TO 9/30/85
- **14. DATE OF REPORT** *(Yr., Mo., Day)*: 29 November 1985
- **15. PAGE COUNT:** 38
- **16. SUPPLEMENTARY NOTATION:**
- **17. COSATI CODES**

FIELD	GROUP	SUB. GR.

- **18. SUBJECT TERMS** *(Continue on reverse if necessary and identify by block number)*: Heat transfer, Pulsating flow, Turbulent flow, Tubes, Boundary layers, Gas turbine systems, Forced convection, Heat Exchangers, Laminar flow, Augmentation, Enhancement, Brayton cycle, Dissociating gases, Rough walls, Complex flows
- **19. ABSTRACT** *(Continue on reverse if necessary and identify by block number)*

For application to gas turbine cycle and Rankine cycles in Naval propulsion, measurements and analyses have been conducted of the following topics: heat transfer to mixtures of gases; heat transfer to pulsating, turbulent gas flow, dissociating gas power cycles; heat transfer at a smooth-to-rough transition; numerical prediction of flow and heat transfer from ribbed surfaces; turbulent heat transfer in a swirl flow downstream of an abrupt pipe expansion and heated, laminarizing gas flows.

- **20. DISTRIBUTION/AVAILABILITY OF ABSTRACT:** UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS ☐
- **21. ABSTRACT SECURITY CLASSIFICATION:** Unclassified
- **22a. NAME OF RESPONSIBLE INDIVIDUAL:** M. K. Ellingsworth
- **22b. TELEPHONE NUMBER** *(Include Area Code)*: (202) 696-4403
- **22c. OFFICE SYMBOL:** ONR 1132p

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified

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SUMMARY

Background

Current naval propulsion plants are powered by variations of the Rankine cycle (steam) or the open gas turbine cycle (air and combustion products), plus some diesel engines in small ships. Alternative power systems suggested include the closed gas turbine cycle and cycles involving dissociation of the working fluid in either a Rankine or a gas cycle. These latter two are believed to offer the potential of substantial improvement in the power-to-weight ratio of the propulsion plant. The studies conducted considered basic problems in convective heat transfer and flow friction that are important in all of the above.

Convective heat transfer provides the dominant thermal resistance in several components of conventional steam power plants, as well as in all heat transfer components in gaseous cycles. For example, the overall thermal resistance from the condensing steam to the cooling water in the main condenser of a naval ship is dominated by the convective thermal resistance of the cooling water inside the tubes [Marto and Nunn, 1980]. One can expect significant reductions in tube length and, therefore, size and weight of the condenser and overall plant if the convective heat transfer coefficient of the cooling water side is increased appreciably. Likewise in the superheater of a

conventional naval steam generator, calculations for typical conditions show that the dominant resistance is the forced convection on the outside of the tubes and, of the two modes, convection is more important than radiation [Harrington, 1971]. The flow in this case is complicated since the Reynolds number is relatively low and--due to the large temperature difference--the gas properties vary through the boundary layer by a factor of two. Again, improvement in this convective heat transfer and its prediction can provide reductions in size and weight of the unit.

The convective heat transfer coefficient can be improved by disrupting the smooth surface by adding various roughness elements which cause increased mixing in the viscous layer (so-called laminar sublayer and buffer layer) [Bergles, 1978]. It has also been suggested that vigorous mixing, induced by artificially roughened surfaces, can also combat fouling in sea water flows through marine condensers. In the case of a gas, dissociation leads to higher heat transfer coefficients. Since the optimization of dissociating gas power plants depends on the recombination of the fluid in a regenerative heat exchanger or a cooler, roughening the surface has also been suggested as a means of improving the recombination rate, as well as enhancing the reduced heat transfer coefficients.

In order to assess the benefits of roughness elements on the inside of condenser tubes or outside of superheater tubes or

other components, in inhibiting fouling and in enhancing recombination in dissociated gases, it is necessary to develop reliable prediction methods for computing the flow field, heat and mass transfer rates and chemical reaction rates to compare proposed rough surfaces to smooth surfaces.

The advantages of adding a low molecular weight gas to one of high molecular weight, to provide a gas mixture with low Prandtl number, in a closed gas turbine (Brayton) cycle can include potential optimization of the heat exchange equipment and turbo-machinery, improvement of heat transfer properties, reduction of impurities and elimination of combustion products which can contaminate blades and surfaces. But it is also of interest to note that the University of Dayton Research Institute is develop-ing a Rankine cycle engine utilizing the mixing of a gas of light molecular weight with a heavy fluid [Mech. Eng., Dec. 1979] in order to improve efficiency and increase operating life.

In a study of potential working fluids for power cycles, McKisson [1954] pointed out the advantages of utilizing the endothermic nature of some dissociation reactions to increase the energy absorbing capacity of the fluid. Pressler [1966] and Callaghan and Mason [1964] and others have shown in early measurements that the convective heat transfer coefficient may be improved as well. For use in a power cycle the dissociated fluid must recombine in another component, typically in a regenerative heat exchanger, cooler or condenser. Thus heat transfer with

both dissociation and recombining fluids is of importance. Our Professor Perkins [Serksnis et al., 1978] has noted the benefits of using the dissociating fluid in the turbine. Bazhin et al., [1970] have examined gas and gas-liquid cycles using dissociating working media to determine the effect of parameters on power plant efficiency, particularly for fast nuclear reactors; N_2O_4, Al_2Cl_5 and Al_2Br_6 received primary interest.

Haynes [1970] reports the following advantages of dissociating power cycles:

1. Compared to steam turbines, the N_2O_4 cycle requires 4 to 5 times less metal investment,
2. At 520-540°C and 130-170 atmospheres, the efficiency of the N_2O_4 cycle is greater than similar cycles of CO_2, H_2O, He and others, and
3. Analyses carried out show the possibility of a substantial improvement (by 20-30%) in the technical-economic indices of fast gas cooled reactors using N_2O_4 compared with atomic electric stations using sodium.

The potential benefits for ship propulsion are obvious. However, with the emphasis to date concentrating on improved efficiency, it is now necessary to examine the thermodynamic cycles to deduce the ranges of operating parameters which lead to optimization of the power-to-weight ratio in naval ships.

A common geometry recurring in compact naval propulsion plants is a change in duct size in the primary fluid loop. As a consequence of the upstream plumbing, the fluid is often swirling about the axis in the piping. Heat losses from the primary fluid and thermal stresses in the component depend on the convective heat transfer from the fluid to the component as it undergoes this geometrical transition. The idealized problem is a study of heat transfer in a sudden expansion with swirl flow. The numerical analyses employed in examining the detailed flow about roughness elements have features in common with this problem, so it has also been studied as an extension of previous work.

Heat Transfer to Mixtures of Gases

In addition to other applications, mixtures of inert gases can be used to improve performance in closed gas turbine cycles. In our early work, heat transfer and wall friction parameters were obtained numerically to demonstrate the effects of mixture composition and gas property variation for heating or cooling in regenerative heat exchangers of such cycles; the situation was modeled by laminar flow through short ducts with constant wall heat flux [McEligot, Taylor and Durst, 1977]. For design predictions accounting for the effect of property variation, it was found that the property ratio method is better than the film temperature method for heat transfer, while the latter method is preferrable for apparent wall friction--with

the proviso that specific definitions of the nondimensional parameters be employed.

Numerical predictions for turbulent flow in circular tubes at low heating rates showed that accepted empirical correlations might overpredict heat transfer coefficients significantly for helium-xenon mixtures. However, the numerical predictions themselves were found to be strongly dependent on the choice among turbulence models which have been hypothesized by various authors.

For comparison to the predictions and correlations, measurements of heat transfer and pressure drop were obtained in a smooth, electrically heated, vertical circular tube with air, helium, a helium-argon mixture and a hydrogen-carbon dioxide mixture with molecular weights ranging from 14.5 to 29.7 for temperatures from about 75° to 1040° F and Reynolds numbers of 8000 to 125,000 [McEligot, Pickett and Taylor, 1976; Serksnis, Taylor and McEligot, 1978; Pickett, Taylor and McEligot, 1979]. The Prandtl number was varied from 0.34 to 0.7 by varying the mixture composition. Popular existing experimental correlations, developed using gases with Prandtl numbers of the order of 0.7, were found to overpredict the observed Nusselt numbers, thereby confirming our earlier numerical predictions. By comparison of numerical calculations and measured constant property Nusselt numbers, turbulent Prandtl numbers were determined in the wall region. For the range of Prandtl numbers examined it was found

that $Pr_{t,wall} = 1.0 \pm 0.1$. The validity of using these deduced turbulent Prandtl numbers was also confirmed for conditions where the properties vary significantly.

In order to conduct measurements at lower Prandtl numbers, the apparatus was modified to a closed loop configuration to contain expensive mixtures of xenon with helium or hydrogen. Initial experiments using a commercial gas booster pump for circulating the gas showed a substantial reduction of mean heat transfer parameters when the pulsations were superposed on the main flow. By adding plenum chambers and more pressure regulators, the percent oscillation was reduced to near steady flow. Experiments in the modified apparatus extended the Prandtl number range down to 0.16 with a hydrogen-xenon mixture.

At a Prandtl number of about 0.2, the predictions of accepted correlations for heat transfer in fully established tube flow differ by a factor more than two. By mixing helium with xenon, or hydrogen with xenon, the range $0.16 \lesssim Pr \lesssim 0.7$ can be obtained. Measurements with these mixtures in a vertical tube showed that the Colburn analogy and Dittus-Boelter correlation substantially overpredict the Nusselt number for constant property conditions; best agreement was provided by relations suggested by Petukhov and by Kays, as in Figure 1 [Taylor, Bauer and McEligot, 1984, 1985]. For moderate variation of gas properties ($1 \lesssim T_w/T_b \lesssim 2.2$) the correlation for average friction factor by Taylor was verified; the exponent on the Prandtl number

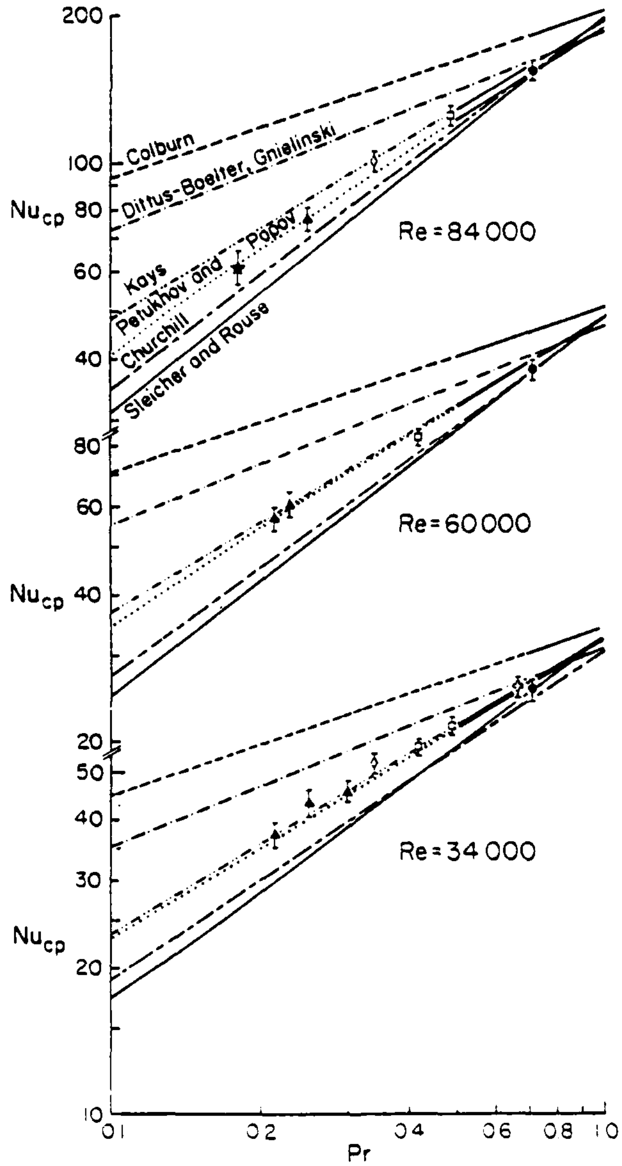

Figure 1. Measured Nusselt number compared to predictions from correlations proposed by other investigators for constant properties [Taylor, Bauer and McEligot, 1985].

in his equation for heat transfer was modified to 0.65 to accommodate these new data.

<u>Heat Transfer to Pulsating, Turbulent Gas Flow</u> [Park, Taylor and McEligot, 1982a,b]

Heat transfer to pulsating flow occurs frequently in practice; one example is in flow systems with reciprocating compressors. However, recent theoretical and experimental investigations of heat transfer to fluids in pulsating flow have led to numerous contradictions.

The major objective of the experiment was to investigate the effects of flow pulsations on heat transfer in the thermal entry region for turbulent gas flow at a moderate Reynolds number in a circular tube. Local heat transfer measurements for pulsating flows were compared to those with steady flow at the same conditions in a smooth, electrically heated, vertical tube. Pulsations were generated by a reciprocating gas compressor which was located upstream of the measuring test section.

Mass flow rates were calculated from measurements with positive displacement meters at the exit of the flow section after cooling and throttling. Simultaneous recordings of pressure and pressure drop were obtained at locations between the test section and the reciprocating pump to measure the wave form of the pulsation. The accuracy of the data was confirmed by tests in turbulent flow without pulsations, but

this study concentrated on direct comparisons between the two situations.

Inlet Reynolds numbers varied from 19,000 to 102,000; Mach numbers were 0.15 or below; pulsation frequencies ranged from 2.1 to 3.6 Hz and the peak-to-peak pressure fluctuations varied from 9 to 29 percent of the mean pressure. At these conditions the nondimensional frequency $\alpha = \sqrt{2\pi f/\nu}$, varied from about 4 to 7-1/2; in laminar flow, quasi-steady approximations become weak when this frequency becomes greater than about two, but for turbulent heat transfer in this Reynolds number range the limitations are still to be determined.

Direct comparison showed all pulsating data to agree with the corresponding values for steady flow within 7-1/2 percent. For Re $\gtrsim 5 \times 10^4$ the pulsating measurements essentially confirmed quasi-steady analyses, which predict a slight reduction in heat transfer parameters, within the reproducibility of the experiment. At lower Reynolds numbers the reduction was larger and increased as α was increased.

Dissociating Gas Power Cycles

Power cycles using gases which dissociate at relatively low temperatures, such as N_2O_4, have been recommended for large central station power plants [Krasin, 1970]. The main advantages have been mentioned in the preceding summary. To date most interest has concentrated on prediction of the thermal efficiency of the plant. We considered application to shipboard power

plants and examined effects on the power-to-weight ratio of a potential plant [Postan, 1982]. The objective of these studies was to determine the approximate operating parameters of a naval propulsion plant using the cycle, so that basic research on convective heat transfer to dissociating/recombining gases could be directed towards the appropriate ranges.

Thermodynamic data for the chemically-reacting nitrogen tetroxide system in chemical equilibrium were fitted to simple relations. These relations were used to provide approximate estimates of the power-to-weight ratio, network output per unit mass of fluid flowing and thermal efficiency of a gas power plant using an idealized representation of N_2O_4 as the working medium. Compared with predictions for air as the working fluid, the results indicated larger power-to-weight ratios and larger specific net work for pressure ratios from 0 to 60 and turbine inlet temperatures from 850 to 1200K. Preliminary predictions showed the weight of components could be reduced to the order of one-half to one-third by using dissociating N_2O_4.

Heat Transfer at a Smooth-to-Rough Transition

Convective heat transfer in turbulent flow can be enhanced by disrupting the viscous sublayer to cause increased turbulent mixing in the boundary layer. The viscous sublayer disruption can be accomplished by surface roughness element of various geometries and patterns. Although past experiments have

shown that rectangular rib elements can enhance heat transfer parameters by a factor of two or three, there are currently no suitable means of predicting such enhancement without experimentation. Further, the effects of property variation coupled with the roughness elements are not well known.

For a number of applications enhancement is only necessary locally along the flow channel; therefore, the experiment examined the transition from a smooth, heated surface to a rough one [McCullough, 1985]. A rough surface of transverse rectangular ribs was studied. Air passed through a rectangular duct with an aspect ratio greater than 12 and, therefore, was idealized as two-dimensional flow between flat plates. Flow was asymmetric since only one plate had roughness elements and heating. The duct consisted of an adiabatic smooth section of 36s) in length (s = spacing) for flow development, followed by a heated section of 12s constructed from smooth plate, 12s with roughness elements, and a final 12s of smooth plate. The test apparatus was designed for optimal rib height, $h^+ \approx 20$, at a Reynolds number of 20,000. The apparatus was also built for a maximum wall-to-inlet temperature ratio of four to examine effects of air property variation.

Measurements for a Reynolds number range of 10,000 to 20,000 have been conducted. The data were used to evaluate the local Nusselt number as a function of heating rate and Reynolds number. These experimental results are compared to numerical

predictions based on the program of Schade and McEligot [1971], which uses a van Driest turbulence model and turbulent Prandtl number to model the boundary layer in the smooth sections of the duct, in Figure 2. In the rough section, the van Driest mixing length model is no longer appropriate near the wall, so a mixing length model using a roughness Reynolds number, Re_k, is used.

The data clearly indicated an increase in Nusselt number resulting from the roughness elements, as expected. Temperature profiles along the test surface showed a reduction in the rate of temperature increase or, for the higher Reynolds number runs, a decline in temperature through the rough section. This observation demonstrates an improved heat transfer coefficient in the rough area over the smooth area. The effect was more pronounced at the upper end of the Reynolds number range. In the vicinity of the smooth-to-rough transition, augmentation of heat transfer parameters was moderated by streamwise conduction in the test plate.

<u>Numerical Prediction of Flow and Heat Transfer from Ribbed Surfaces</u> [Faas and McEligot, 1980]

Currently, development of optimal rough surfaces for a given application is a time-consuming process requiring extensive experiments. In order to reduce the number of experiments required, we developed numerical prediction methods by extending an existing program for two-dimensional recirculating flows, "TEACH" [Gosman and Ideriah, 1976].

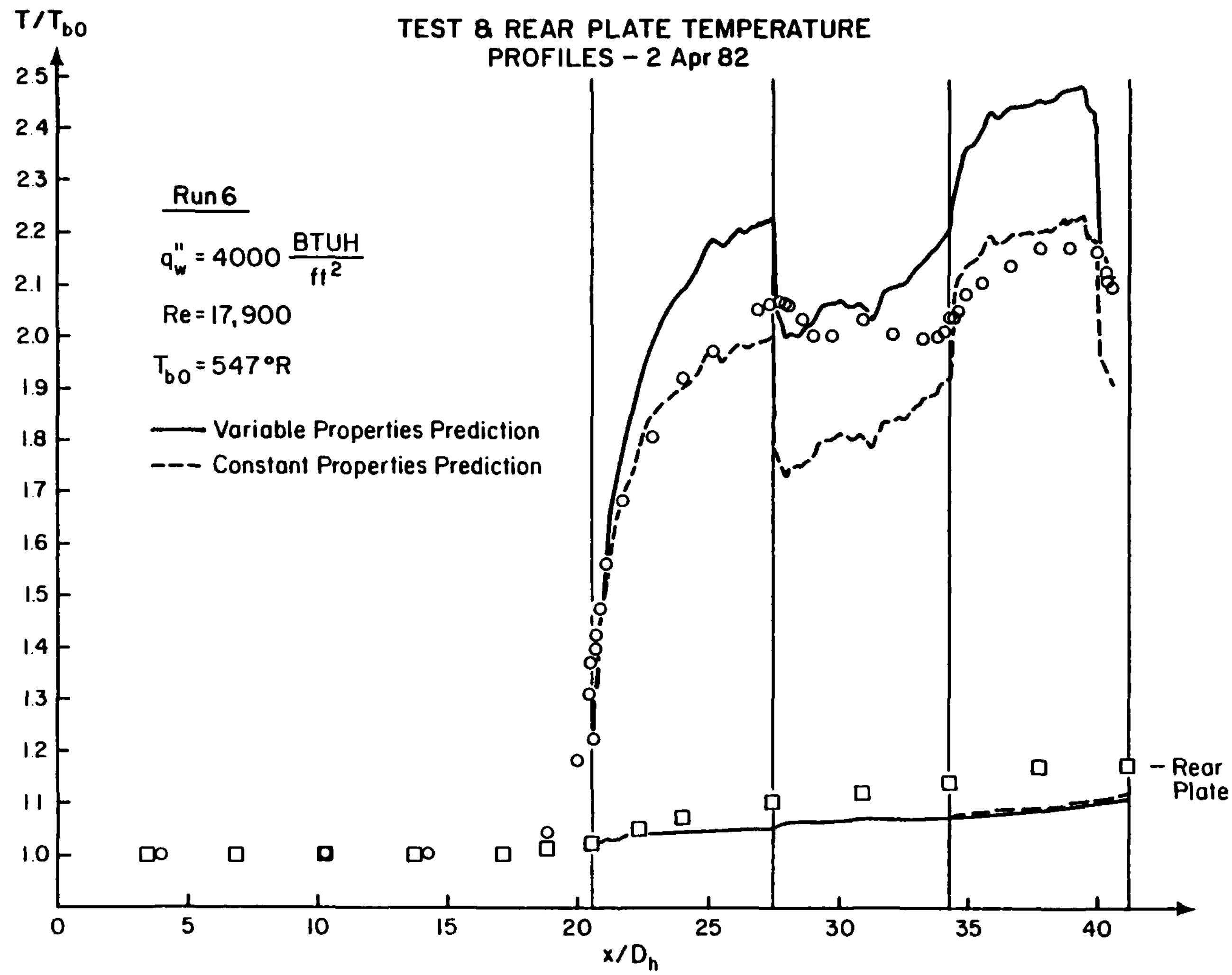

Figure 2. Measurements of heat transfer at smooth/rough/smooth transition [McCullough, 1985].

Short [1978] modified the "TEACH" program to treat flow around a rectangular rib with periodic boundary conditions consistent with the spatially periodic disturbance of the flow by the ribs. His preliminary study was confined to laminar flow but considered dimensions of the same order as would be appropriate for turbulent flow to test scaling difficulties.

Since applications to practical power cycles will likely require materials such as stainless steel--which has a low thermal conductivity--and the flow conditions plus roughness geometry will be chosen for improved convective heat transfer, the thermal resistance in the solid wall may approach that of fluid. Consequently, the general problem is one of coupled convection and conduction. To accommodate both resistances, Short extended the numerical method to solve the energy equation in both the fluid and the wall, simultaneously.

Short's flow results appear good and his thermal results show the correct trends. The locations of the maximum and minimum wall temperatures, as well as the maximum and minimum heat transfer coefficients, are reasonable and agree with published data and calculations.

Faas [1979] extended the study of Short; two geometries were treated: flow in a corrugated duct, as for a plate-fin heat exchanger, and flow over surfaces with repeated ribs to improve heat transfer to gases. Initial attempts to impose the boundary conditions by a version of a generalized Newton-Raphson method

were unsuccessful, but a more direct iterative technique, referred to as the "internal plane method," worked well. Essentially, the numerical grid covers two unit cells and trial boundary conditions are held constant until the iterative solution approaches convergence. The solution at an internal plane, which is either identical to the boundaries or an image plane, is then applied as the next estimate of the boundary values and the procedure is repeated.

For flow over repeated ribs in a two-dimensional duct, predictions were made at Re = 400 and Pr = 0.7 including treatment of the thermal conduction problem in the plate. Dimensions corresponded to the design of our rough wall test section with air taken as the fluid and stainless steel as the wall material. Average results were Nu = 8.45 and f = 0.70 compared to 8.24 and 0.060, respectively, for a smooth wall. Other results are presented in an earlier annual report [Faas and McEligot, 1980].

<u>Turbulent Heat Transfer in a Swirl Flow Downstream of an Abrupt Pipe Expansion</u>
[Habib and McEligot, 1981, 1982]

The problem of improving the heat transfer in circular ducts is of great importance in the engineering field; its application is found, for example, in heat exchangers and combustion systems. Two cases in which heat transfer is augmented are swirling flows and flows downstream of a sudden pipe expansion. In both cases, separation and swirl cause high shearing rates

which are associated with 1) high rates of generation of turbulence kinetic energy and 2) increase in the length scales which lead to a reduction in the rate of dissipation of turbulence kinetic energy. All these features reduce the viscous sublayer through which heat must pass largely by molecular diffusion. These two cases have been rarely studied numerically. The combined effect of swirl and abrupt enlargement on heat transfer parameters apparently had not been studied before our investigation.

Our study developed numerical predictions of flow and heat transfer downstream of a sudden expansion applied to turbulent swirl flow in a pipe. The calculations were obtained by the numerical solution of the time-averaged forms of the continuity, momentum and thermal energy equations together with transport equations for the kinetic energy of turbulence and its rate of dissipation. The effect of body forces due to streamline curvature on turbulence was taken into consideration by specifying one of the empirical constants in the dissipation equation as a function of the flux Richardson number [Bradshaw, 1973].

For the case of a sudden expansion without swirl, prediction for the experiment of Zemanick and Dougall [1970] produced satisfactory agreement with measured local Nusselt numbers. For the swirling case there were no data available for comparison; however, the measurements of Beltagui and

MacCullum [1976] for a sudden expansion with swirl, but without heat transfer, were used to obtain confidence in the results of the flow field calculations.

The calculations encompassed the effects of swirl and Prandtl number on heat transfer parameters for swirl flow down-stream of an abrupt pipe expansion, with a constant wall temperature as the thermal boundary condition. They were made for ranges of swirl number from 0.0 to 1.0 and of Prandtl number of 0.7 (air) to 10 (water). The effects of the swirl number on the velocity and temperature fields were also determined. The results predicted that as the swirl number increases, the Nusselt number will increase near the expansion and the position of its maximum value will move towards the inlet section. At downstream locations and low swirl numbers, the Nusselt number appeared to decrease slightly with an increase in the swirl number. The results also suggested that increasing the Prandtl number will increase the local Nusselt number.

Heated, Laminarizing Gas Flows

Measurements of mean velocity and mean temperature fields and wall parameters for air flowing in a smooth, vertical tube at low entry Reynolds numbers were obtained for heating with constant wall heat flux along the heated length [Shehata, 1984]. Two entry Reynolds numbers of approximately 6,000 and 4,000 were employed with three heating rates, $q^+ = q_w/(Gc_{p,i}T_i)$, of 0.0018, 0.0035 and 0.0045 approximately. The flow development was

measured by obtaining internal profiles along the heated length at axial locations from 3.2 to 24.5 diameters. An adiabatic entry of 50 diameters preceded the heated region. The three heating rates caused slight, large and severe property variation of the air. The highest heating rate was found to cause significant buoyancy effects.

The internal measurements were obtained using constant temperature hot-wire anemometry and resistance thermometry for velocity and temperature, respectively, employing a single short wire probe. A technique was developed and employed for the use of a single short hot wire in velocity measurements in non-isothermal flows.

The measurements were compared to numerical predictions employing two simple versions of the van Driest mixing length turbulence model, Figure 3. In general, both models agreed with the measurements reasonably well, but for the higher heating rates neither model was completely satisfactory in predicting the velocity profiles. When the buoyancy parameter reached 0.3, the peak velocity occurred in the wall region rather than at the tube centerline. Typically, the Nusselt number was overpredicted by 10% for $x/D > 14$ and, consequently, the wall temperature was underpredicted by about 7%.

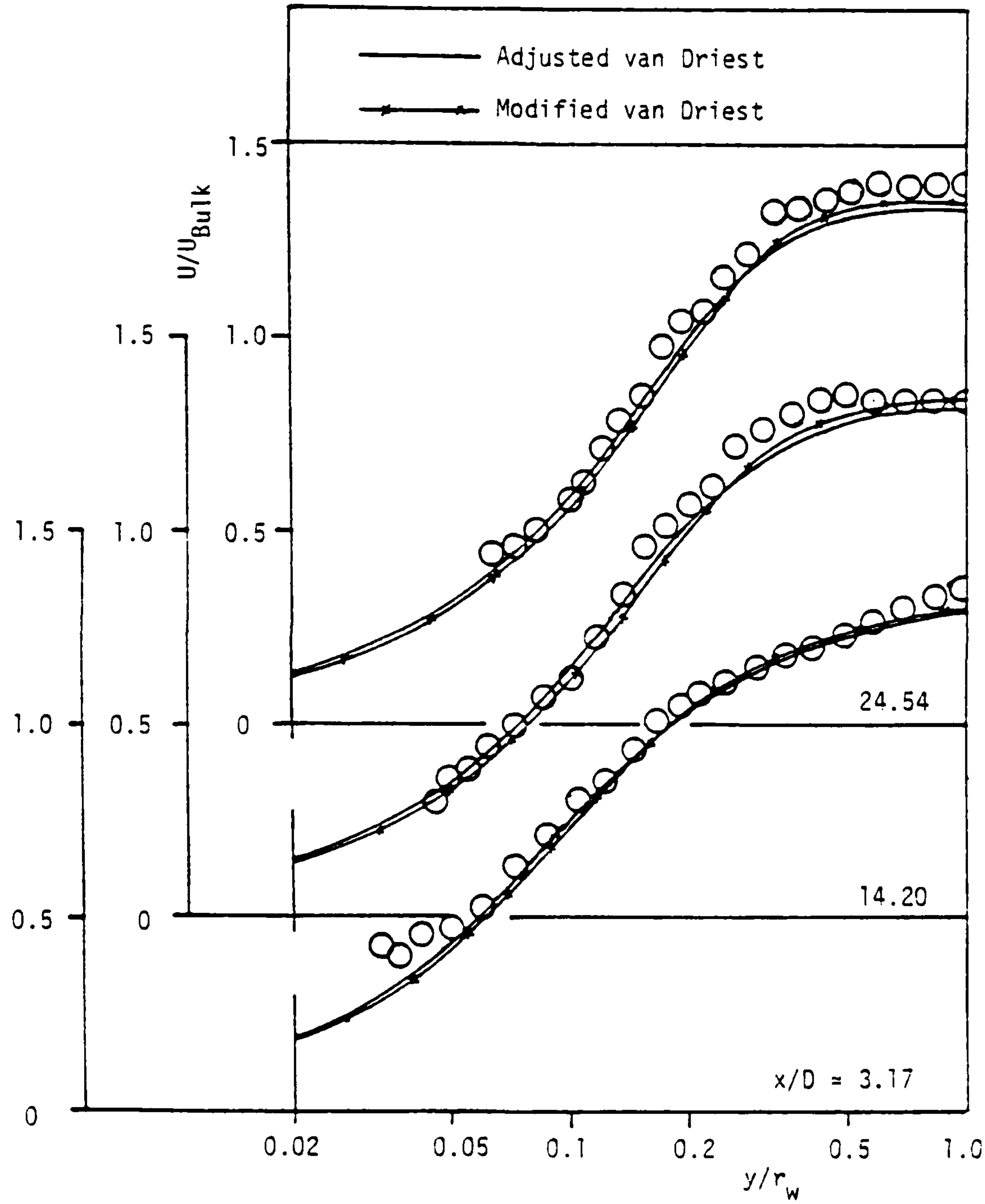

Figure 3. Axial momentum development presented in stretched coordinates. $Re_i \approx 4{,}000$; $q^+ \approx 0.0045$ [Shehata, 1984].

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